Improved explicit ground water recharge and discharge simulation methods for the Pitman model – explanation and example applications.

D.A. Hughes[1] and R. Parsons[2]

[1] Institute for Water Research, Rhodes University, Grahamstown, South Africa
[2] Parsons & Associates Specialist Groundwater Consultants, Somerset West, South Africa

Abstract

A procedure for incorporating SW-GW interactions into the monthly Pitman rainfall-runoff model was presented at the 2003 SANCIAHS Symposium. The initial algorithms were limited to situations with permanent contributions of ground water to streamflow and did not allow for any evaporative losses from the riparian channel margins. Revised algorithms include evaporation from riparian areas, downstream GW outflows and allow for situations where GW levels can fluctuate between losing and gaining systems. Consequently, channel transmission losses are accounted for, both from sub-catchment generated runoff, as well as from upstream flows. The final improvement is the allowance for GW abstractions. The details of the model are briefly presented, as well as a critical evaluation of several applications. The examples cover a range of catchment response types and the model results are largely evaluated on the basis of intuitive understanding of the prevailing processes in each catchment, supported by any existing quantitative information that is available to calibrate the model or validate the results.

Keywords: Rainfall-runoff models, ground-surface water interactions.

1 Introduction

The first version of the revised Pitman model with more explicit ground water interaction routines was presented at the SANCIAHS 2003 and subsequently published (Hughes, 2004). The original model focussed on the recharge and ground water discharge (to streamflow) components and assumed that the ground water level was always above the channel (or at the same level). The model has now been through several testing phases and development iterations to account for other processes and to be made applicable to more catchment situations than the first version. The additional components focussed on allowing for situations where the ground water level could drop below the river channel through riparian evaporation losses and sub-surface outflow to down-gradient catchments, as well as accounting for abstraction losses. One consequence of allowing for the ground water to drop below the channel was that channel transmission losses could play an important role in the overall water balance.

One of the important consequences of making any changes to a model that is in regular use, is the need to offer guidelines for parameter estimation and how the new version of the model affects parameter values associated with older versions. This is particularly relevant to the Pitman model that has formed the basis for the national database of simulated naturalised monthly flows through WR90 (Midgley et al., 1994) and will continue to do so through the next revision (WR2005 – a current Water Research Commission project). In this regard Conrad (2005) has compiled a very useful database of new and existing ground water related information that has the potential to form the basis for estimating some of the parameters of the revised Pitman model.

2 Brief Description of the Model

Space does not permit a full description of the new model algorithms and therefore this section of the paper will be limited to a brief description of the main components, the new parameters and possible sources of information for quantifying the parameters. The new model components can be divided up into seven groups:

- Recharge estimation.
- Ground water storage geometry.
- Evaporation losses to riparian vegetation.
- Ground water contribution to streamflow.
- Ground water discharge to downstream sub-catchments.
- Channel transmission losses.
- Abstractions.

2.1 Recharge Estimation

Recharge estimation is based on the same type of non-linear power function as the original model approach to estimating soil moisture runoff (Figure 1). A new parameter GW represents the maximum monthly recharge rate (at moisture level = ST), while GPOW represents the rate of decline of recharge as the catchment dries out and SL represents the moisture level at which recharge ceases.

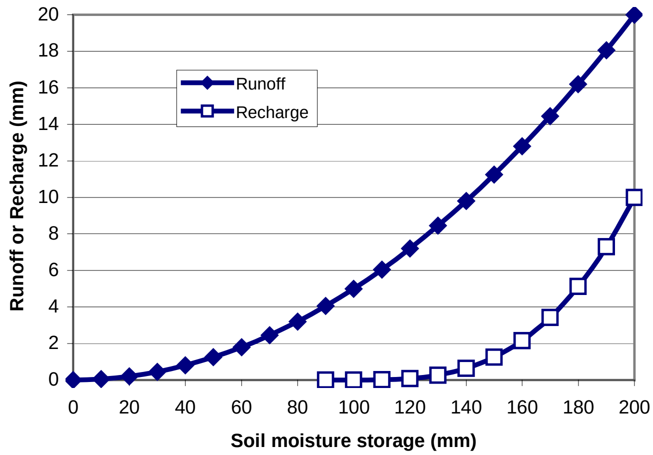

Figure 1. Illustration of the original soil moisture runoff function (parameters ST=200, SL=0, FT=20 and POW=2) and the new recharge-moisture state relationship (parameters SL=100, GW=10 and GPOW=3).

Typically, the type of information that is available about recharge (Conrad, 2005) is a mean annual value and it is very difficult to use such a value to estimate the parameters GW, GPOW and SL. The approach for calibrating these parameters is therefore to manually adjust them until a satisfactory mean annual recharge value is obtained (i.e. one that matches an independent assessment of recharge). Unfortunately, a simple mean annual recharge estimate does not help very much with determining the balance between the three parameters, however, there is very little existing information on time series variations in recharge.

2.2 Ground Water Storage Geometry

The Pitman model is a relatively simple conceptual water balance model based on sub-catchment scales. It would therefore be inappropriate to link a ground water model to it that is vastly more complex than the original model. For this reason the sub-surface geometry of the revised model has been kept simple and is based on dividing the catchment up into an even number of conceptual slope elements each of which flows toward half the same number of channels.

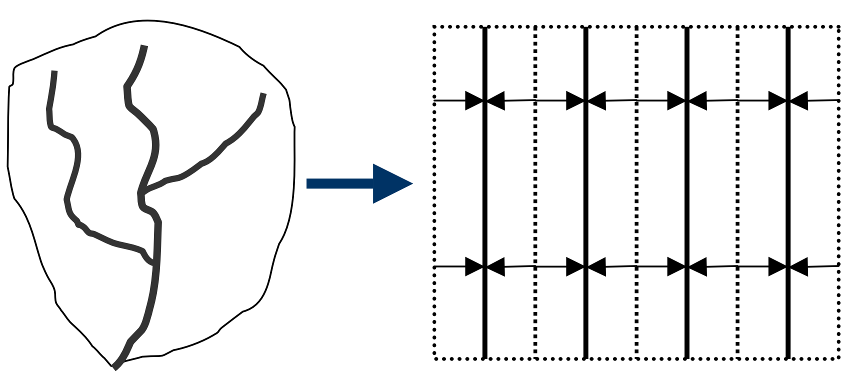

Figure 2. Plan geometry arrangement based on a number of slope elements draining to channels.

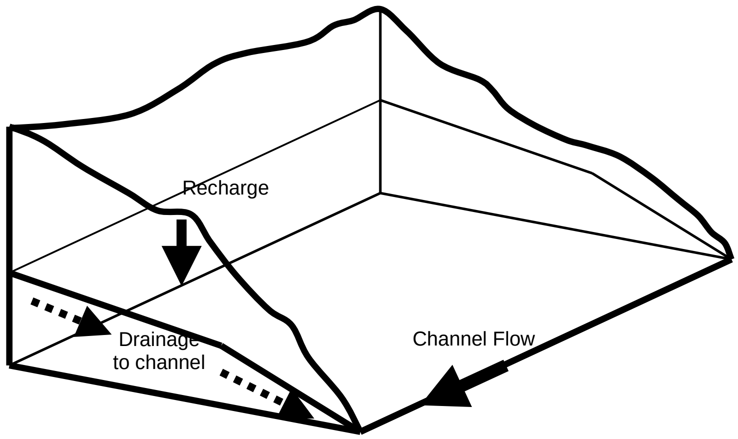

Figure 3. Geometry showing a single slope element and channel combination and illustrating the two drainage gradients.

The sub-catchment is conceptualised as a rectangle with the width/length ratio and number of channels (Figure 2) determined by an 'effective drainage density' parameter. Within each slope element that drains toward a channel the ground water storage 'wedge' is made up of two components; an upper component (remote from the channel) and a lower component draining directly into the channel (Figure 3). Two gradient components are used to allow for differences in abstraction effects depending on the location of the boreholes with respect to the channel. The drainage density parameter should be based on the number of channels that are actively receiving ground water, rather than any other definition of drainage density. The model results can be relatively sensitive to this parameter and yet it is difficult to develop guidelines for its estimation. A default value of 0.4 has been used, while long, thin catchments and arid areas are assumed to have lower densities.

The ground water balance calculations are based on monthly volume inputs from recharge and channel transmission losses, as well as outputs due to contributions to streamflow, down-catchment drainage and losses to riparian evaporation. A storativity parameter is used to convert the water losses into geometric volume after which the new gradients of the ground water storage 'wedge' are calculated. One end of the lower component gradient is fixed at the channel and the other based on the volume in the lower (close to the channel) storage zone. The upper (remote from the channel) component gradient is then estimated from its volume and the common point at which the two gradient lines are joined. The upper component flows into the lower one, while the lower one contributes to streamflow (see next sections). If the outflows are greater than the inflows (in either component) the slopes can become negative. A negative slope in the lower component is conceptually equivalent to a ground water level that is below the channel (a losing stream or gaining ground water situation). The storativity parameter is evaluated directly from regional storativity values given in Conrad (2005).

2.3 Evaporation Losses to Riparian Vegetation

A parameter representing the percentage of the full width of a slope element that will contribute to riparian evaporative losses is included. It is assumed that losses will occur from this at the net potential rate (potential evaporation minus rainfall and not < 0) while the near-channel component gradient is positive and at a lesser rate (down to zero at a 'rest water level' – defined by a parameter value) when the gradient is negative.

2.4 Ground Water Contribution to Streamflow

This is calculated from the gradient of the lower component, a transmissivity parameter and the length of the channel (from the catchment area and drainage density). The default transmissivity parameter values are available from Conrad (2005) after a correction to account for a rate that can be considered applicable at the catchment scale.

2.5 Ground Water Discharge to Downstream Sub-Catchments

This is calculated from a regional ground water gradient, transmissivity and the width of a slope element and applies to both slope components. The transmissivity parameter is reduced as the lateral ground water gradient in the lower slope component becomes negative and is assumed to be zero at the 'rest water level'. Default regional ground water gradients have been estimated from the catchment slope data provided in Conrad (2005), however, the variation between catchments is assumed to be quite small.

2.6 Channel Transmission Losses

This process is notoriously difficult to include in simple, monthly time-step models. The processes are not well understood and observed data are almost non-existent. It has therefore been assumed (pers. comm.. Karim Sami) that the volume of potential transmission loss will be proportional to both:

- The lateral ground water gradient in the lower slope component near the channel (assuming the gradient is negative).
- The volume of water in the channel.

As there is generally no information to quantify the nature of these relationships, their exponents have been fixed in the model and the only parameter is the maximum monthly transmission loss, which will occur when the near channel gradient reaches the rest water level and the flow in the channel is at a maximum (estimated from an initial model run through the complete time series). Figure 4 illustrates the relationships. Figure 4A shows how a variable TLQ increases with increasing runoff, while Figure 4B how a variable TLG increases (to TLGMax) as the near channel gradient becomes increasingly negative. The final value for transmission loss is TLQ * TLG. Two types of channel transmission loss are allowed for. The first is the loss within the sub-catchment from incremental flows (and can be viewed as losses that occur from tributaries within the sub-catchment). The second (and usually the most important) is loss from the main channel that applies to flows generated in upstream sub-catchments.

A B

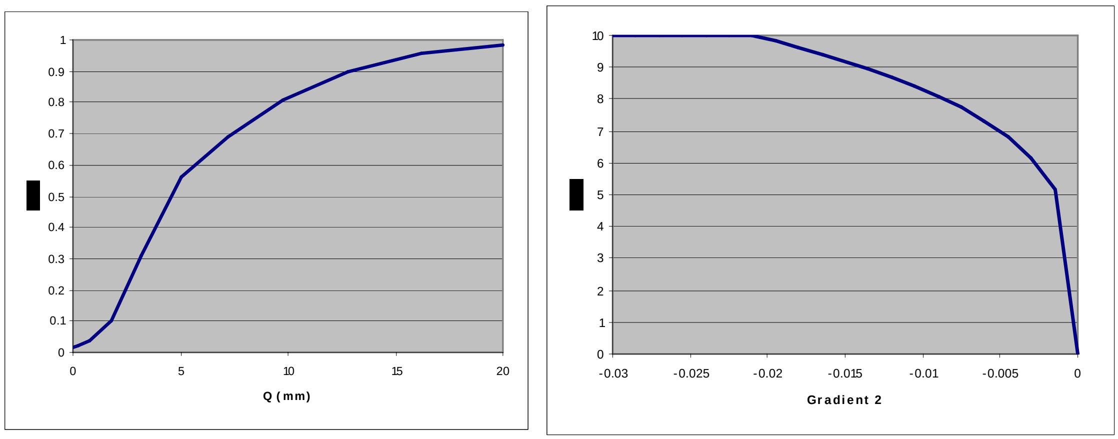

Figure 4: Shapes of the power relationships between (A) current month discharge (mm), relative to a maximum value (20mm in this case) and a model variable, TLQ and between (B) near channel lateral gradient and a model variable, TLG.

2.7 Abstractions

Abstractions are defined by annual volumes and seasonal distributions for both near channel and remote boreholes. The monthly volumes are removed from the two slope components, the geometry re-calculated and the gradients adjusted as part of the normal model water balance calculations. The main consequence of including two slope components is that abstractions from the near channel component have an immediate effect on ground water contributions to streamflow, while those from remote locations have a delayed effect.

2.8 General

The new ground water interaction routines represent a highly conceptualised approach to simulating ground water at the catchment scale. It is recognised that under real-life situations there are variations in the length of the channel network that receives ground water inputs and that the ground water lateral gradient (toward the channels) may not vary as much as the model suggests. However, the simulated variations in ground water gradient are representing all the other 'real' variations that contribute to variations in ground water contributions to streamflow. At the same time, the model formulation allows the simulated water balance calculations to be easily and explicitly converted into variations in lateral gradient. One of the major issues associated with testing the model is to ensure that variations in the values of the model parameters lead to intuitively sensible variations in simulated surface-ground water interactions (Parsons, 2003).

3 Parameter Estimation

Table 1 provides a summary of the quantitative information that is available from the Conrad (2005) database for all 1946 quaternary catchments (Midgley et al., 1994) in South Africa, Lesotho and Swaziland. Table 2 summarises the new parameters and the basis for their initial estimation, using the Conrad (2005) data where appropriate. The first two (SL and GW) were part of the original model and have been re-defined, while the original ground water routing parameter (GL) is no longer considered necessary as the new approach effectively routes recharge through a non-linear storage-discharge function.

It is clear that *a priori* estimates of the recharge parameters (GW, POW and SL) cannot be provided, but that they have to be calibrated against one or more of the Conrad (2005) mean annual recharge estimates. The difficulty is that there is a wide variation in the three Conrad (2005) estimates. The drainage density parameter affects the rate at which ground water drains to the channel system, as well as the volume of outflow to downstream catchments. It is also difficult to determine *a priori* estimates, but is expected to vary within a relatively narrow range of values (0.1 to 0.6). The model results can be very sensitive to the riparian strip factor, in that high values (> 0.5%) can result in most of the lateral drainage to the channel being lost to evaporation.

It is difficult to estimate but should be based on a knowledge of the riparian environment of a specific catchment. It is interesting to note that if the riparian land use is changed (for example through the growth of alien vegetation with high water consumption), this parameter could provide a mechanism for simulating the impacts on streamflow. In catchments with predominantly negative lateral gradients (i.e. ground water levels below the channel), where channel transmission losses are important, the maximum channel loss parameter (TLGMax) will play a major role. As already indicated, these processes are not well understood and it will be necessary to establish procedures for setting the value of this parameter through trial simulations. There is very little information from the application of the original Pitman model that can help with establishing an estimation procedure for this parameter, although studies such as the Limpopo assessment of Boroto and Görgens (2003) may be useful. The typical approach to channel transmission losses in these applications has been to use evaporation from 'dummy dams' and a comparison with the results of applying the new version of the model would be very informative.

Table 1: Data contained within the Conrad (2005) database for all quaternary catchments

CATNUM	WR90 quaternary catchment number
AREA_m2	Area in m^2
CMAP	CMAP from WR90
MAP_MM3	MAP in Mm^3 calculated from CMAP
MAR	MAR from WR90
TOTAL_USE	Total GW use Mm^3 from GRAII
USEOFRECH	Use as a percentage of calculated recharge – in this case the uncalibrated GIS method output
SLOPE	Mean slope per catchment (degrees) calculated from 1x1km grid based on DWAF DTM
MEAN_SLP_P	Mean slope per catchment (percentage) calculated from 1x1km grid based on DWAF DTM
MEAN_SSATI	Mean SSATI per catchment from Vegter's SSATI dataset
MED_SSATI	Median SSATI per catchment from Vegter's SSATI dataset
MEAN_STHK	Mean saturated thickness from Vegter 1995. The mean thickness of that part of the saturated zone which contains the bulk of the most readily accessible groundwater was taken on average to be half the optimal drilling depth below the water level.
MED_STHK	Median saturated thickness per catchment from Vegter 1995
MEAN_TRANS	Mean transmissivity per catchment - Transmissivity (m^2/day) derived from borehole yields (NGDB & Paul du Plessis)
EBFI	Estimated baseflow index
RECHP	Mean calculated recharge % from GRAII - output from GIS calibrated layer
RECH_MM3	Mean calculated recharge vol. from GRAII - output from GIS calibrated layer
RECH_MM_feb05	Mean calculated recharge depth from GRAII - output from GIS calibrated layer
RECHMIN_MM3	Min. calculated recharge vol. from GRAII - output from GIS calibrated layer
RECHMAX_MM3	Max. calculated recharge vol. from GRAII - output from GIS calibrated layer
RECHMIN	Min. calculated recharge % from GRAII - output from GIS calibrated layer
RECHMAX	Max. calculated recharge % from GRAII - output from GIS calibrated layer
RECHRNG	Range of calculated recharge % from GRAII - output from GIS calibrated layer
MIN_KS	Min. calculated recharge % from GRAII - GIS calibrated against K.Sami output
MAX_KS	Max. calculated recharge % from GRAII - GIS calibrated against K.Sami output
MEAN_KS	Mean calculated recharge % from GRAII - GIS calibrated against K.Sami output
MIN_MM3_KS	Min. calculated recharge vol. from GRAII - GIS calibrated against K.Sami output
MAX_MM3_KS	Max. calculated recharge vol. from GRAII - GIS calibrated against K.Sami output
MEAN_MM3_KS	Mean calculated recharge vol. from GRAII - GIS calibrated against K.Sami output
MIN_RDM	Min. calculated recharge % from GRAII - GIS calibrated against output from RDM office
MAX_RDM	Max. calculated recharge % from GRAII - GIS calibrated against output from RDM office
MEAN_RDM	Mean calculated recharge % from GRAII - GIS calibrated against output from RDM office
MIN_RDM_MM3	Min. calculated recharge vol. from GRAII - GIS calibrated against output from RDM office
MAX_RDM_MM3	Max. calculated recharge vol. from GRAII - GIS calibrated against output from RDM office
MEAN_RDM_MM3	Mean calculated recharge vol. from GRAII - GIS calibrated against output from RDM office

Table 2: Parameters of the ground water components of the new model

Parameter and units	Symbol	Estimation approach
No recharge below storage (mm)	SL	Manually adjusted until mean annual recharge matches one or more of the Conrad estimates (RECH_MM3, MEAN_MM3_KS or MEAN_RDM_MM3).
Max. Recharge rate (mm/month)	GW	
Power : Storage-Recharge curve	GPOW	
Drainage density	DDens	Defaults to 0.4, adjusted downwards for long, narrow catchments or arid areas.
Transmissivity (m^2/day)	T	From 0.5 * MEAN_TRANS
Storativity	S	From MEAN_SSATI
Regional GW drainage slope	RG	From (MEAN_SLP_P / 100)$^{0.05}$
Rest water level (m below surface)	RWL	From MED_STHK
Riparian Strip Factor (% slope width)	RSF	Nominally 0.2% and intuitively adjusted on the basis of local knowledge.
Maximum Channel Loss (mm)	TLGMax	Needs to be related to typical runoff depths.
GW Abstraction (Upper slopes-Ml y^{-1})	GWA_upper	From available knowledge of ground water use within the catchment.
GW Abstraction (Lower slopes-Ml y^{-1})	GWA_lower	

4 Initial Model Tests

Several initial model tests have been completed on the basis of comparing the results of the new version of the model with the natural monthly flow time series available within WR90 (Midgley et al., 1994). The main purpose of these tests was to see if the model can reproduce the 'conventional wisdom' that is represented by the WR90 database in terms of baseflow response and the extent to which this can be achieved with the parameter estimation approaches described above. It must be recognised, however, that this implies that any miss-representation of catchment baseflow response by the WR90 data will be carried through into the tests of the revised model.

Initial model tests were undertaken on several catchments that have permanent ground water contributions to streamflow (A91G, E10A,E&K, K90A&D, V60A,D&F, X31A), including one strongly impacted by dolomites (A21B). J25B was included as a catchment with seasonal contributions, while Q92F and Q94F were included to represent drier catchments where ground water contributions are expected to be negligible.

Figures 5 to 7 illustrate the type of results obtained for the wet catchments with strong ground water contributions. X31A is a steep headwater tributary of the Sabie River where both interflow and ground water contributions are assumed to be substantial. Comparisons with WR90 (Figure 5) suggest that the model is readily able to reproduce existing patterns of assumed low flow response, while Figure 6 suggests that the simulated lateral ground water gradients are acceptable for this catchment (given the mean catchment slope of 11.2%). The mean annual recharge (10.9% of rainfall) lies within the range suggested by the three values of the Conrad (2005) database (8.1 to 17.0%) and Figure 7 indicates that the balance between interflow and ground water contribution is intuitively (see Parsons, 2003) acceptable (interflow = 44% and ground water = 25% of total runoff). The results for the other catchments in the 'permanent ground water contribution' category are quite similar, although many of the recharge estimates lie closer to the lower value (usually MEAN_KS) in the Conrad (2005) database. Parameter GPOW was fixed at 3.0 and SL at 0, leaving GW the only recharge parameter to calibrate. T and S were estimated as specified in Table 2, while the default estimates of 0.4 and 0.2 for DDens and RSF, respectively, were found to be generally acceptable. The results for the dolimitic catchments were very poor and this appears to be related to the way in which the original Pitman model was setup for these. This issue requires further investigation as the authors could not explain the discrepancies during the model tests.

J25B represents a semi-arid tributary of the Gouritz River in the Karoo, although the WR90 data suggest that the river is almost perennial with less than 5% zero flows. The pattern of low flows simulated by the new version of the model is almost identical to WR90, while the recharge (1.7%) has been estimated to be higher than the MEAN_KS value of 0.9%, but lower than the other two recharge estimates (4.2 and 6.4%). The Conrad (2005) estimate of T (36 m^2/day) was considered excessive and reduced to 10 m^2/day. As this is a relatively arid area without substantial riparian vegetation the drainage density was set at 0.2 and the RSF parameter at 0.05%. Figure 8 illustrates the patterns of variation of the two lateral ground water gradients, which clearly indicate that most of the time there is a flow of ground water toward the stream. However, for a large part of the time this flow is lost to channel margin evapotranspiration and the final result is that about 24% of the recharge emerges as streamflow.

Both Q92F and Q94F are semi-arid catchments in the Eastern Cape experiencing periodic flow and are not expected to have significant ground water contributions to streamflow. Q94F is at the downstream end of the Kat River and has much wetter catchments upstream. The importance of simulating the ground water conditions correctly relates, in part, to the extent to which upstream inflows will be reduced through channel transmission losses. It is therefore important that the TLGMAX parameter is set correctly. The pattern of simulated monthly flows for the new version of the model agrees very well with the WR90 data.

Figure 9 illustrates the variations in simulated ground water lateral gradients for Q92F and the lower gradient is positive for 36% of the total 70 year period, while ground water contributions to streamflow are positive for only 5% of the time. The assumption is that ground water is draining to the channel (and possibly recharging channel pools) for a much longer period of time than flow exists in the channel. This is consistent with an intuitive understanding of the role of ground water in some semi-arid systems (Hughes, 2005). The simulated recharge estimates for Q92F and Q94F are approximately 1% of mean annual rainfall, which lies between the lowest Conrad values (0.2%) and the higher ones (6.4%). The higher estimates are not considered to be appropriate to these regions.

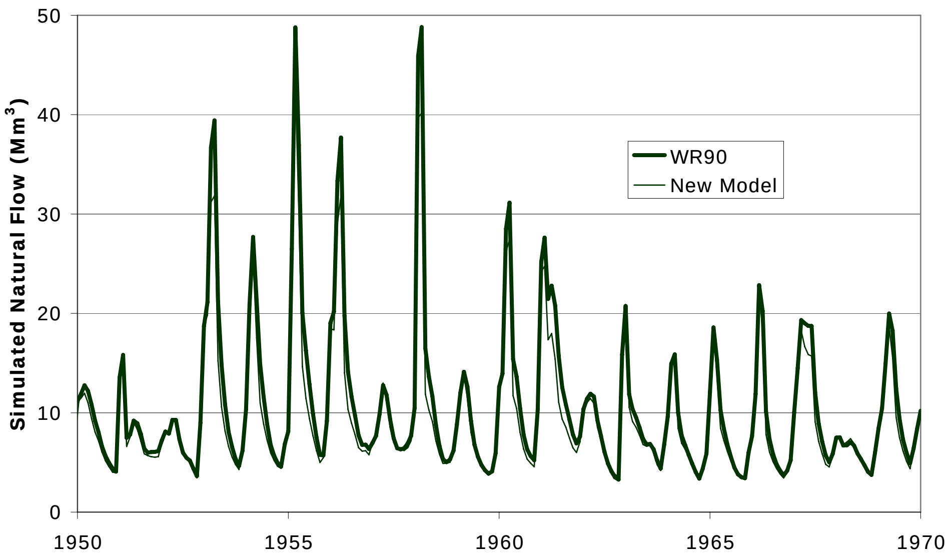

Figure 5: Comparison of WR90 and new model simulated natural flows for quaternary catchment X31A

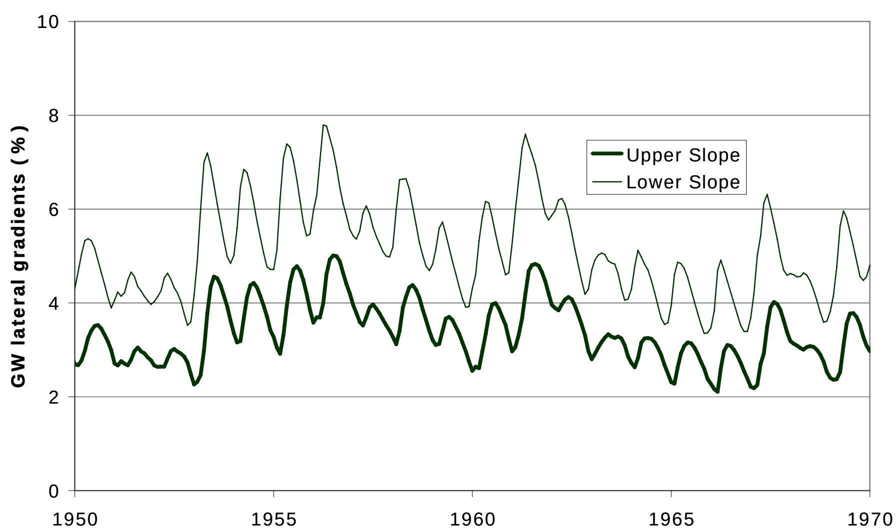

Figure 6: Comparison of upper (remote from channel) and lower (close to channel) simulated lateral GW gradients for quaternary catchment X31A

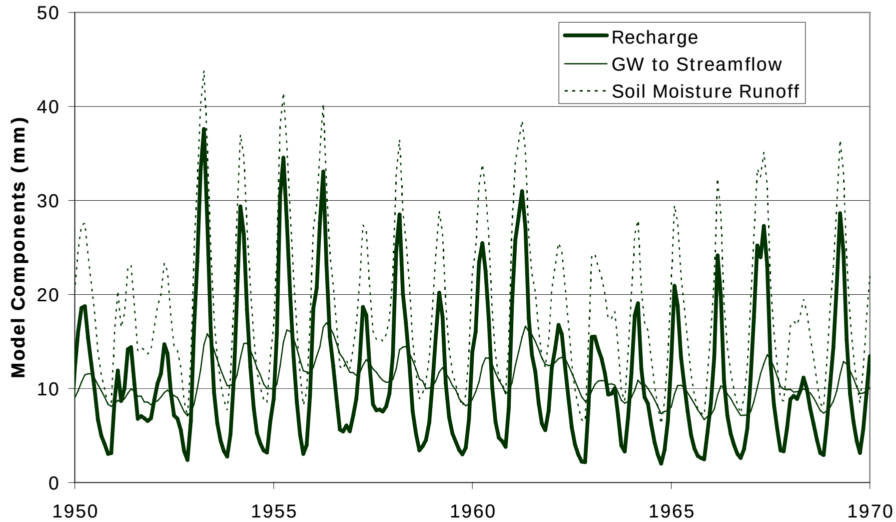

Figure 7: Comparison of simulated recharge, GW contribution to streamflow and soil moisture runoff for quaternary catchment X31A

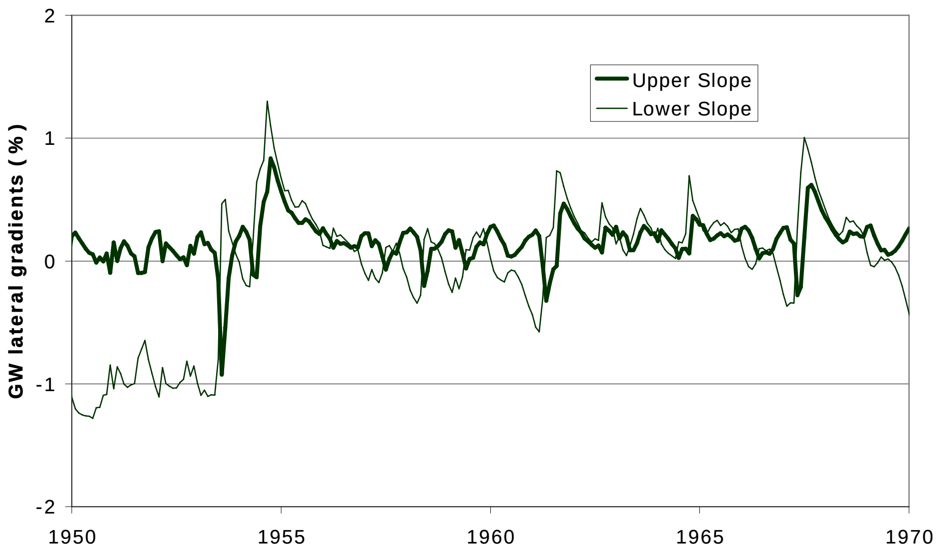

Figure 8: Comparison of upper (remote from channel) and lower (close to channel) simulated lateral GW gradients for quaternary catchment J25B

As with J25B, drainage density values lower than the default of 0.4 were used (0.1 for Q92F and 0.2 for Q94F), while the RSF parameter was set at 0.1% for Q92F. The default RSF factor of 0.2% was used for Q94F although further work is required to determine the impact of this decision on channel transmission losses of upstream inflows. The estimated catchment average T value from the Conrad database for Q92F (41.8 m^2/day) was considered too high and reduced to 5 m^2/day. The calibrated parameter values and the results generated by the new version of the model are generally consistent with detailed field observations of the surface and ground water hydrological characteristics of Q92F (Hughes and Sami, 1991).

Figure 10 illustrates that the simulation of cumulative flows at the downstream end of 6 quaternary catchments (Q94A to F) with a total area of 1715 km^2 and very mixed runoff response characteristics has been successful, relative to the WR90 results.

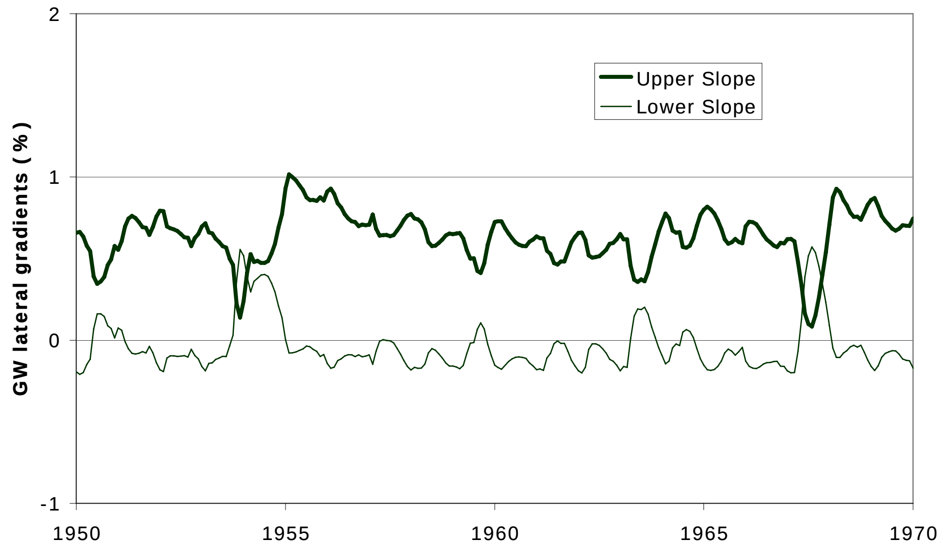

Figure 9: Comparison of upper (remote from channel) and lower (close to channel) simulated lateral GW gradients for quaternary catchment Q92F

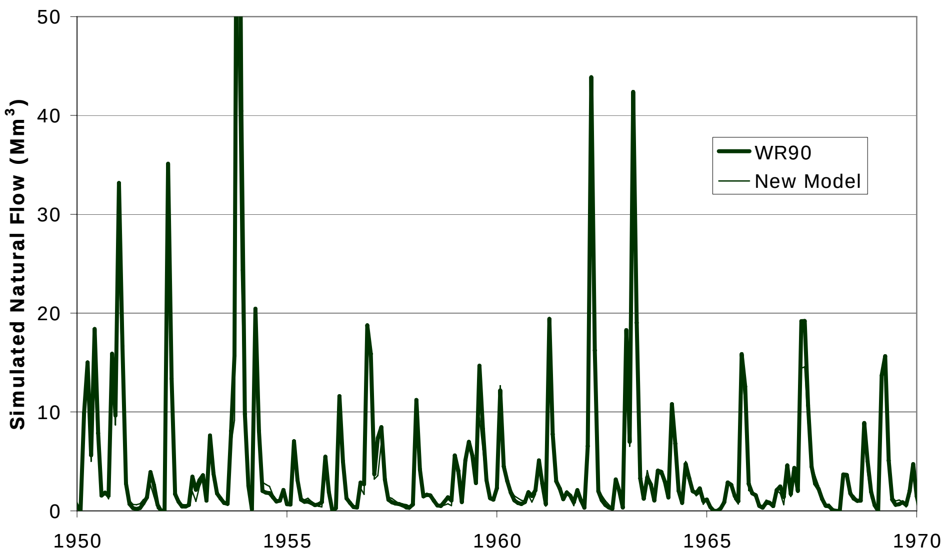

Figure 10: Comparison of WR90 and new model simulated natural flows for quaternary catchment Q94F

5 Discussion and Conclusions

In almost all of the test catchments the revised model could be calibrated to reproduce very similar patterns of simulated monthly flow as represented by the WR90 data and this could be achieved with intuitively sensible parameter values, many of which could be estimated from the Conrad (2005) database. The exceptions to this rule were those catchments dominated by dolomitic influences that appear to have received special attention during the WR90 application of the original Pitman model. It is impossible to conclude at this stage which type of baseflow response (represented by the outputs from the two models) is the most realistic as there is a general lack of observed data for these dolomitic areas. This issue requires further attention and if resolved could contribute to a better understanding of how the parameters of the new version of the model should be quantified in certain catchment situations.

One of the issues that also requires further investigation is the difference between the three recharge estimates that are contained within the Conrad (2005) database. It will always be confusing to potential users of the new version of the model if there are three possible recharge estimates to calibrate the model against. The initial tests have found that the higher estimates (usually the RECHP values) generate far too much recharge and subsequent ground water contribution to streamflow unless the riparian strip factor parameter is set very high so that a much higher proportion of the recharge is lost to evaporation. More acceptable recharge estimates appear to lie between the MEAN_RDM and MEAN_KS values (see Table 1) given in the database.

The original T values in the Conrad (2005) database have been divided in half for use in the model, in recognition that catchment average transmissivity values will be smaller than those based on observations from individual pumping tests. It is generally accepted that T values vary considerably at the catchment scale, but that it is very difficult to determine the range of variation without far more measurements than are currently available.

In the original Pitman model the only drainage output (evapotranspiration losses also occur) from the soil moisture storage is controlled by the soil moisture runoff function (Figure 1) and parameters FT and POW. The ground water runoff component in the original model formed part of that runoff (i.e. it was not simulated in addition). In the new version of the model there are now two outputs, ground water recharge (that eventually becomes ground water contribution to streamflow) and soil moisture runoff. It might therefore be expected that the parameters controlling soil moisture should be reduced to accommodate the runoff generated through the recharge component. However, in most of the test simulations it was not found necessary to reduce parameter FT. It appears that the additional drainage that occurs as recharge reduces the soil moisture storage level in each model iteration such that soil moisture runoff is reduced without having to modify the original values of the FT parameter. There were, however, several catchments where a small reduction in FT improved the results (based on correspondence between the revised model outputs and WR90 simulated flows).

It was noted earlier that there are uncertainties about the validity of the WR90 simulated low flows in some areas and that testing the revised model against these data is not a very thorough evaluation. This is accepted by the authors and it should be recognised that the initial tests were undertaken to discover if 'conventional wisdom' could be reproduced by the revised model with intuitively reasonable parameter values. The results are very encouraging and the tests can be considered successful in all catchments except those dominated by dolomitic ground water effects.

The disadvantage of the revised model is clearly the greater number of parameters that have to be quantified. However, this is an inevitable consequence of adding a more explicit approach to simulating hydrological processes. The advantage is that users are able to examine and interpret the components of total flow in a more detailed way to determine whether they are being generated for the right reasons. It is accepted that there is frequently very little observed information available about catchment scale surface-ground water interaction processes and intuitive evaluations are often necessary. However, the new version of the model opens the door for further joint investigations based on modelling, detailed field observations and runoff component tracer studies, all of which have the potential to improve our understanding of the interactions.

Acknowledgements

The Water Research Commission contributed to some of the model development and to the model tests through project K5/1498. Karim Sami contributed to many of the discussions that were held about the development of the model and was largely responsible for the channel loss algorithms. Thanks are due to Julian Conrad for providing the quaternary catchment information for all the variables listed in Table 1.

References

Boroto, R.A.J. & Görgens, A.H.M. 2003. Estimating transmission losses along the Limpopo River. Hydrology in the Mediterranean and Semi-arid Regions. IAHS Publ. No 278: 138-143.

Conrad, J. 2005. Preparation and production of a series of GIS-based maps to identify areas where groundwater contributes to baseflow (WRC Project Number K5/1498). GEOSS Report No. G2005/02-1

Hughes, D.A. 2004. Incorporating ground water recharge and discharge functions into an existing monthly rainfall-runoff model. Hydrol. Sci. Journ. 49(2), 297-311.

Hughes, D.A. 2005. Hydrological issues associated with the determination of environmental water requirements of ephemeral rivers. River Research and Applications (Accepted for publication, November 2004).

Hughes, D.A. & Sami, K. 1991 The Bedford Catchments. An Introduction to their Physical and Hydrological Characteristics. Unpublished report to the Water Research Commission. Institute for Water Research, Rhodes University, Grahamstown.

Midgley, D. C., Pitman, W. V. & Middleton, B. J. 1994. Surface Water Resources of South Africa 1990, vols I–VI. Water Research Commission Reports nos 298/1.1/94–298/6.1/94, Pretoria, South Africa.

Parsons, R. 2003. Surface Water: Groundwater Interaction in a South African Context – A Geohydrological Perspective. Water Research Commission Report No. TT 218/03, Pretoria.